

# PATENT SPECIFICATION

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## (54) IMPROVEMENTS IN OR RELATING TO STEPPER MOTORS

(71) We, ULTRA ELECTRONICS LIMITED, Western Avenue, Acton, London W.3, A British Company, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

The invention relates to an electrical stepper motor excitation circuit.

Conventional stepper motors are driven so that the rotor moves according to the number of magnetic poles in discrete steps. It has so far been impossible to positively locate the rotor at a position intermediate to the stable positions determined by the number of magnetic poles and their location on the stator. Because of the discrete movements of the stepper motor the positional resolution of the output from a gear train is determined by the gearing ratio and the magnitude of the discrete steps.

In certain applications, such as on aircraft, the positional resolution desired has required additional gearing which is costly and adds to the size and weight of the system, both of which are at a premium in modern aircraft.

It is an object of the present invention to provide an excitation circuit for a stepper motor which enables the discrete stepping characteristic of a conventional stepper motor to be eliminated so giving complete positional control of the rotor.

According to the present invention there is provided an electrical stepper motor excitation circuit comprising means for positioning the motor rotor intermediate two poles of the motor by modulating electrical excitation applied to the poles so that the mean torque on the rotor falls towards zero as the rotor approaches the desired position intermediate the two poles.

The invention will be described by way of examples with reference to the accompanying drawings, wherein:—

Figure 1 is a diagrammatic illustration of an electrical stepper motor and excitation circuit in accordance with the invention;

Figure 2 is a partly schematic circuit diagram of an electrical stepper motor and part of another excitation circuit in accordance with the invention;

Figure 3 is a circuit diagram of another part of the excitation circuit of Figure 2; and

Figure 4 is a schematic diagram of the stepper motor in Figure 2.

Referring to Figure 1 there is shown an oscillator 1 driving a winding 2 on the central limb 3 of a magnetic position sensing arrangement 4. The magnetic circuit from the limb 3 is complete via a soft iron vane 5 and the limbs 6, 7 and 8 according to the position of vane 5. Windings 9, 10 and 11 are mounted on the limbs 6, 7 and 8 respectively so that the modulated magnetic field in the position sensing arrangement induces a signal in the windings the magnitude of which signal is dependent upon the degree of coupling between the central limb 3 and the equispaced peripheral limbs 6, 7 and 8. The vane 5 is mounted on a motor driven shaft 12 so that the positional information derived from the windings 9, 10 and 11 represents the position of the rotor of the stepper motor (shown schematically as 13). The motor speed demand signal is applied to the drive coils 14 from a terminal 15 via three amplifier arrangements 16, 17 and 18 connected to the position sensing arrangement 4 by the windings 9, 10 and 11 respectively.

The vane 5 is profiled in its shape so that the overlap of the limbs 6, 7 and 8 is such that the windings 9, 10 and 11 are intermittently energised to drive the coils 14 so as to produce a magnetic vector which corresponds to the sum of the drive currents produced by the amplifiers 16, 17 and 18. By varying the currents in the drive coils the resultant vector can be varied continuously through 360° so eliminating the discrete steps generally produced by the switched drive current.

Referring to Figures 2 and 4 there is shown a three-phase electrical stepper motor 20 having three poles 21, 22 and 23 with respective

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stator windings 21', 22' and 23' spaced 120° apart around a permanent magnet rotor 24 which is integral with a shaft 25. A gear 26 on the shaft 25 meshes with a gear 27 on a shaft 28 which is connected through a transmission device shown schematically at 29 to a tapping 30 of a potentiometer 31, so that the rotor 24 drives the tapping 30. Terminals 32 and 33 of the potentiometer 31 are connected to zero and +10 volts supply potentials respectively, so that the output on the tapping 30 varies between 0 and +10 volts as the rotor 24 rotates. The angle through which the rotor 24 has to rotate to drive the tapping 30 from one end to the other of the potentiometer may be greater than, equal to or less than one complete revolution.

A second potentiometer 34, for example, has terminals 35 and 36 connected to 0v and -10 volt supply potentials and a variable tapping 37 which can be driven externally, (that is, for example manually or by some other device not shown), to produce a signal between 0 and -10v.

A comparison circuit 38 comprises an output terminal 39 (Figures 2 and 3) connected through resistance R1 to a tapping 30. Tapping 30 is connected through capacitance C1 and through resistance R2 to tapping 37. Resistance R3 connects resistance R2 to a supply potential of +5 volts. The potential at terminal 39 is variable between -10 volts and +10 volts according to the positions of tappings 30 and 37.

A ferromagnetic vane 40, (like the vane 5 in Figure 1), is mounted on shaft 25 and co-operates with a magnetic sensing arrangement 41, (like the magnetic sensing arrangement 4 of Figure 1), comprising windings 42, 43, 44 and 45 (corresponding to windings 2, 11, 12 and 13 in Figure 1). The winding 42 is electrically connected to and energised by an oscillator 46 (corresponding to oscillator 1 in Figure 1). More particularly, winding 42 is connected to a secondary winding 47 of a transformer 48 having a tapped primary winding 49 connected to the collectors of NPN type transistors X14 and X15 of the oscillator 46, which also comprises resistances R4 and R5 and capacitance C2, as well as a tertiary winding 50 of transformer 48, connected as shown, and oscillates at 30 kilohertz.

Windings 43, 44 and 45 are respectively connected to the bases of NPN type transistors X5, X6 and X7. A biasing potential of +5 volts is applied to the bases of these transistors X5, X6 and X7 from a terminal 51 through windings 43, 44 and 45 and part of winding 42. Because the voltage induced in each one of windings 43, 44 and 45 when the respective limbs of the core, (not shown but corresponding to the limbs 6, 7 and 8 in Figure 1), are completely uncovered by the

vane 40 is not zero but 20% of the voltage induced when the respective limbs are completely covered by the vane, the junction of windings 43, 44 and 45 is connected not to one end of winding 42 but to a point 20% along winding 42 from one end, so that the potential at the bases of transistors X5, X6 and X7 is a substantially steady +5 volts when the respective limbs are uncovered and only alternates about this level when the respective limbs are covered. Since the vane 40 is semicircular, the sequence of conduction is X5, X5+X6, X6, X6+X7, X7, X7+X5, X5 for one direction of rotation of vane 40, in six steps of 60° per revolution, and the reverse sequence for the other direction. To control the direction of rotation of motor 20, the transistors X5, X6 and X7 are connected to a pair of transistors X3 and X4 and through them to another pair of transistors X1 and X2. Transistors X1 and X2 are connected to transistors X14 and X15 respectively so as to conduct alternately for respective half cycles of the oscillation frequency, whilst transistors X3 and X4 are connected respectively to terminals 52 and 53 (Figure 2 and Figure 3). A potential of +5 volts at terminal 52 produced by the circuit shown in Figure 3 causes rotation (or at least torque) in one direction, whilst a potential of +5 volts at terminal 53 (instead of terminal 52) produced by the circuit shown in Figure 3 causes rotation (or at least torque) in the opposite direction. Due to the action of transistors X1 and X2, transistors X5, X6 and X7 phase-sensitively demodulate the voltages on windings 43, 44 and 45 respectively. Capacitances C3, C4 and C5 are storage capacitances for transistors X5, X6 and X7 and drive transistors X8, X9 and X10 so that, whereas conduction of each of X5, X6 and X7 is discontinuous at a pulse frequency equal to the oscillation frequency, conduction of each of transistors X8, X9 and X10 is continuous for the duration that the vane 40 covers the respective limb of the core. Transistors X8, X9 and X10 respectively drive transistors X11, X12 and X13 which energise three lines 54, 55 and 56 through diodes D1, D2 and D3. Lines 54, 55 and 56 are connected to the three stator windings 21', 22' and 23' respectively. Transistors X11', X12' and X13' are connected as shown because the junction of stator windings 21', 22' and 23' is not accessible. The circuit in Figure 2 also comprises zener diodes Z1 and Z2 developing 4.7 volts and 3.3 volts respectively, resistances R3 to R24 and capacitances C2 to C5, connected as shown. Resistances R10 to R15 enable any two of transistors X8, X9 and X10 to conduct and saturate even if the drives to them are not quite equal.

The component values and types in Figure 2 are as follows:—

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Motor 20—Muirhead size 08;			
Transistors			
X1	Type LDA-400	X9	Type LDA-450
X2	"	X10	"
5 X3	"	X11	Type BFX84
X4	"	X12	"
X5	"	X13	"
X6	"	X11'	"
X7	"	X12'	"
10 X8	Type LDA-450	X13'	"
Resistances			
R1	10 kilohms	R13	5.6 kilohms
R2	10 "	R14	5.6 "
R3	1 "	R15	5.6 "
15 R4	9 "	R16	500 ohms
R5	9 "	R17	500 "
R6	100 "	R18	500 "
R7	10 "	R19	820 "
R8	10 "	R20	820 "
20 R9	100 ohms a.o.t. (adjust on test)	R21	820 "
R10	10 kilohms	R22	500 "
R11	10 "	R23	500 "
R12	10 "	R24	500 "
Winding Turns			
25 Winding 42	has 450 turns;		
" 43	" 330 "		
" 44	" " "		
" 45	" " "		
30 " 47	" 22 "		
" 49	" 100 turns in each half;		
" 50	" 4 turns.		
Capacitances			
C1	10 $\mu$ F	C4	1 $\mu$ F
35 C2	0.01 $\mu$ F	C5	1 $\mu$ F
C3	1 $\mu$ F		

Supply potentials of 28 volts, 12 volts and 0 volts are applied to terminals 57, 58 and 59 respectively.

- 40 Referring to Figure 3, there is shown a variable mark/space ratio pulse generator 60 which receives an input at terminal 39 from comparator 38 and supplies outputs at terminals 52 and 53 to transistors X3 and X4 in Figure 2. The generator 60 comprises resistances R1' to R11', capacitances C1' to C4', zener diodes Z1' and Z2', and integrated circuit amplifier 61 type  $\mu$ A709 and transistors X16 and X17 type 2N3702, connected as shown. Zener diodes Z1' and Z2' in series develop 3.3 volts. Supply potentials of +5 volts and 0 volts are applied respectively to terminals 62 and 63. Resistance and capacitance component values are as follows:—

Resistances			
55 R1'	4.7 kilohms	R7'	115 kilohms
R2'	3.9 "	R8'	12 "
R3'	410 ohms	R9'	10 "
R4'	39 kilohms	R10'	12 "
60 R5'	220 ohms	R11'	10 "
R6'	390 kilohms		

Capacitances			
C1'	0.5 $\mu$ F	C3'	0.02 $\mu$ F
C2'	3900 pF	C4'	330 $\mu$ F

The circuit of Figure 3 operates in different ways at different levels and is best understood by starting with low level signals.

Suppose a small positive step input signal  $V_{in}$  is present at terminal 39, and that C3' is temporarily shorted out. To a first approximation R1', R4', R6' and the amplifier 61 form a feedback amplifier circuit and the output voltage from the amplifier is defined by resistor ratios. When the step occurs C1' starts to charge exponentially to—

$$V_{C1'} = V_{in} \cdot \frac{R4'}{R1' + R4'}$$

and the amplifier output goes towards

$$V_{a1} = V_{C1'} \cdot \frac{R6'}{R4'}$$

If this is less than the combined conduction voltage of the zener diodes Z1' and Z2' nothing further happens. If it is greater then the positive feedback chain R3', R5' causes the amplifier to switch to maximum negative. This has two other effects. It applies a negative charging current to C1' via R2' and it causes X16 to conduct giving an output of +5 volts at terminal 53.

The negative charging of C1' eventually overcomes the input signal and the positive feedback voltage so that the zener diodes Z1' and Z2' cease conducting, the positive feedback voltage disappears and the amplifier output goes positive, (causing X16 to switch off and X17 to conduct), to a degree depending on the feedback step etc. C1' then charges positive again from the input signal and the cycle repeats. The more positive, or "higher", the input signal the shorter the time C1' takes to charge until eventually C1' cannot be biased sufficiently negative via R2' and X16 becomes permanently biased. If the input is negative the process is similar but as the amplifier goes positive X17 gets turned on permanently instead of X16, producing +5 volts at terminal 52.

While C3' is shorted out no signal occurs for small error signals. If C3' is put back into circuit integrating, action takes place for small errors giving a very low mark/space eliminating dead band.

For satisfactory action the following equations should be observed:—

$$\frac{R2'}{R1'} < \frac{V5 - V2}{V_{in}}$$

where V5 and V2 are the voltages at terminals 5 and 2 of amplifier 61, to ensure discharge of C1';

$$\frac{R5'}{R3' + R5'} > \frac{R6'}{R4'}$$

5 for latching; and  $(R3' + R5') < R2'$  to avoid input driving R2'.

Thus if for a given setting of tapping 37 the tapping 30 is positioned so that there is a relatively large positive or negative voltage at terminal 39, circuit 60 produces continuous +5 volts at terminal 53 or 52 respectively, resulting in continuous torque on rotor 24 in the direction required to reduce the voltage at terminal 39 towards zero by driving tapping 30. As the voltage at terminal 39 approaches zero instead of transistor X16 (or X17) conducting continuously, transistors X16 and X17 conduct alternately so that the instantaneous torque on rotor 24 alternates, the net mean torque depending on the ratio, (the "mark/space" ratio), between the periods of conduction of X16 and X17, this ratio approaching unity as the voltage at terminal 39 approaches zero, so that the net mean torque on rotor 24 falls to zero.

In an alternative arrangement the vane 5, shown in Figure 1, may be gradually varied in air gap or reluctance so that drive signals to the poles vary continuously, and a magnetic vector is produced which is exactly in the desired position.

The described excitation circuits have the advantage that the circuit may be controlled directly by a digital signal derived from a computer.

#### WHAT WE CLAIM IS:—

1. An electrical stepper motor excitation circuit comprising means for positioning the motor rotor intermediate two poles of the motor modulating electrical excitation applied to the poles so that the mean torque on the rotor falls towards zero as the rotor approaches

the desired position intermediate the two poles.

2. An electrical stepper motor excitation circuit as claimed in claim 1 wherein said means comprises a controllably variable mark/space ratio pulse generator and means to excite the two poles intermittently for periods determined by the variable mark/space ratio pulse generator, so that the instantaneous net torque on the rotor alternates and so that the mean net torque on the rotor falls towards zero as the rotor approaches the desired position intermediate the two poles.

3. An electrical stepper motor excitation circuit as claimed in claim 1 or 2 wherein a variable tapping of a potentiometer is arranged to be driven by the motor and is connected to one input of a comparison circuit, another input of which is connected to means for setting a desired position for the rotor, the output of the comparison circuit providing a control signal for modulating said electrical excitation.

4. An electrical stepper motor excitation circuit as claimed in any preceding claim wherein said means for positioning the motor rotor comprises a rotatable ferromagnetic vane arranged to be driven in synchronism with the rotor, a stationary ferromagnetic core having windings thereon corresponding in number to the stator windings, an oscillator arranged to energise said windings on said core, the arrangement being such that the energisation of each winding on the core depends upon the positional relationship of the vane and the core, and an electrical switching circuit connected to the oscillator and to the windings on said core to switch excitation of each stator winding in dependence on the energisation of each winding on the core.

5. An electrical stepper motor excitation circuit substantially as described with reference to Figures 2 and 3 of the accompanying drawings.

MARKS & CLERK

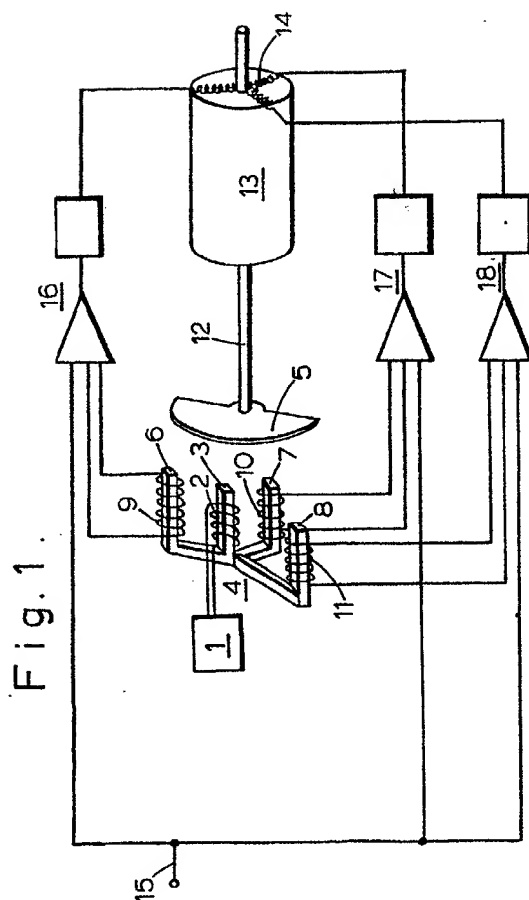


Fig.2.

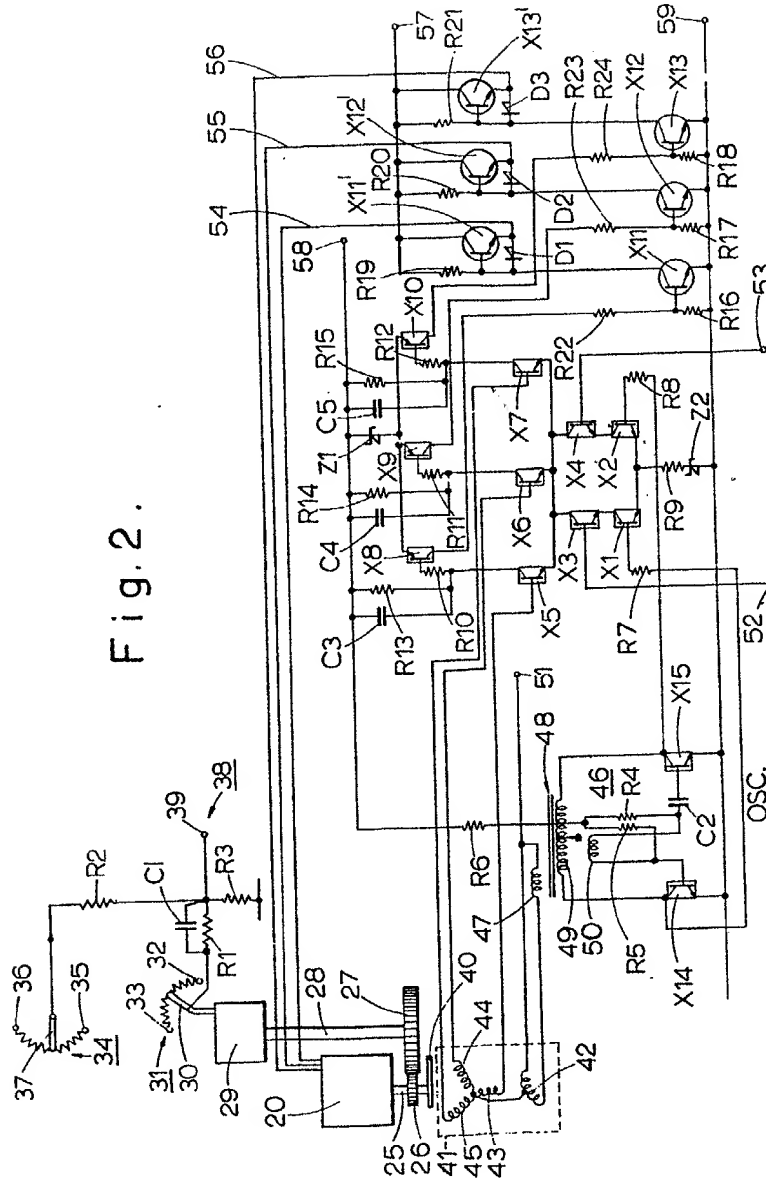


Fig. 3.

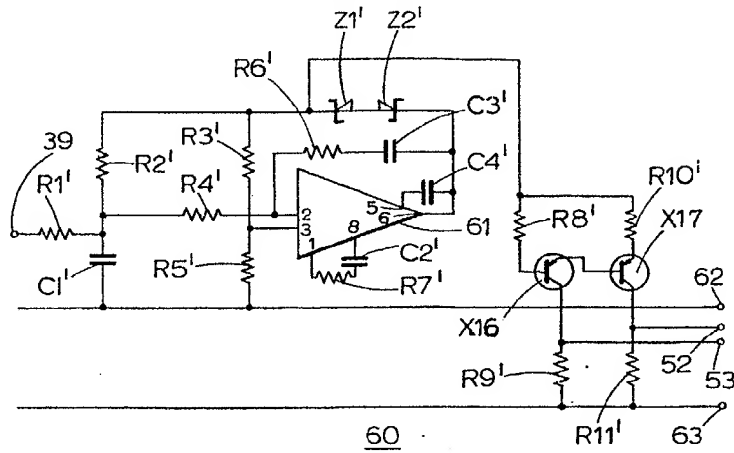
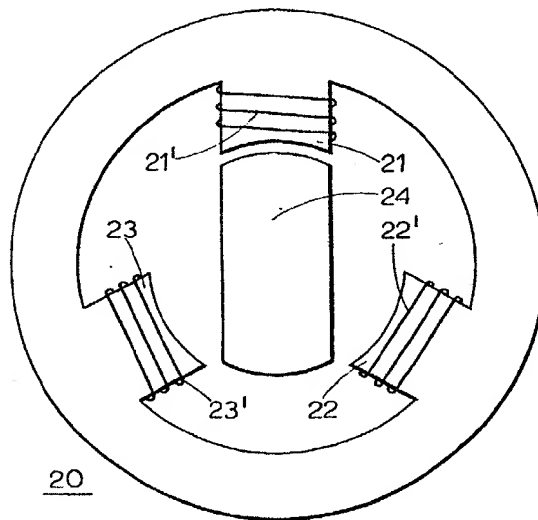


Fig. 4.







1354624 COMPLETE SPECIFICATION

3 SHEETS This drawing is a reproduction of  
the Original on a reduced scale  
Sheet 1

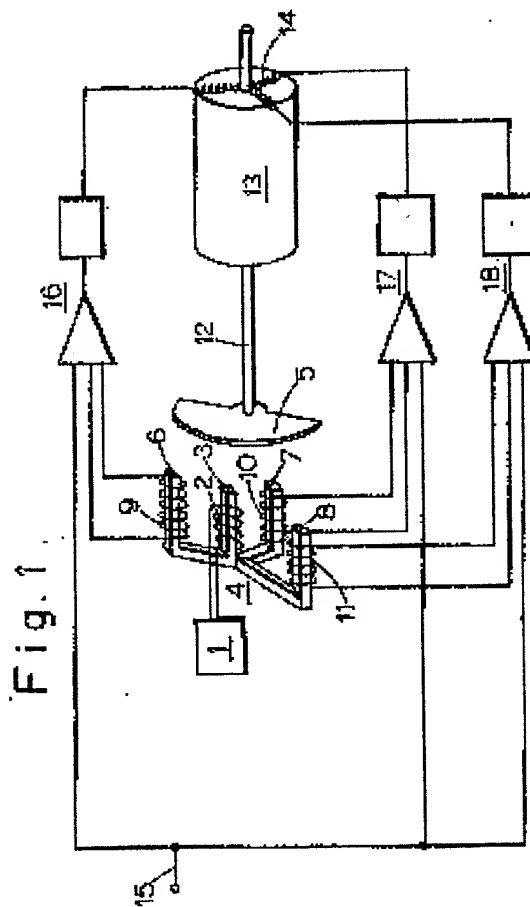


Fig. 2.

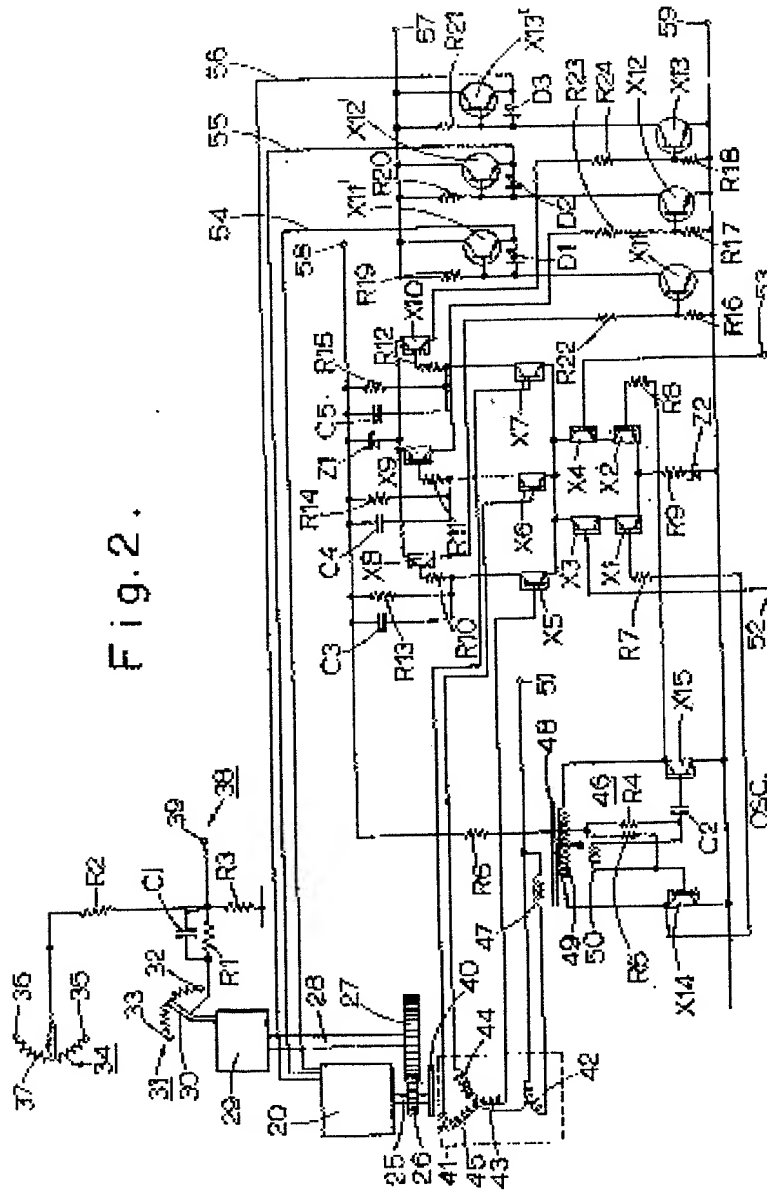


Fig. 3.

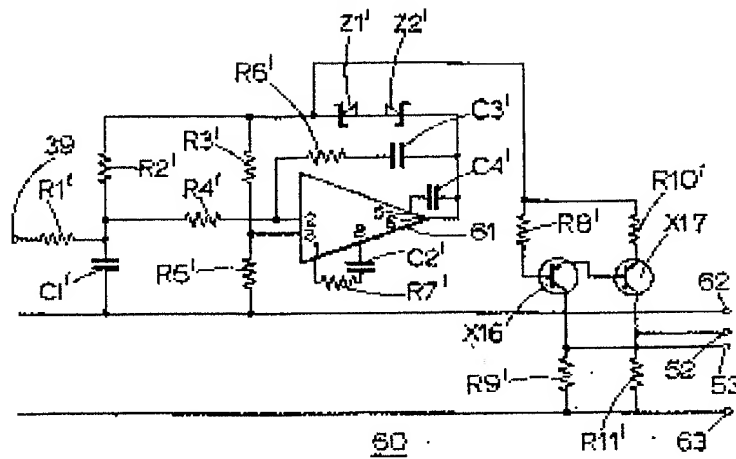


Fig. 4.

